Method for evaluating smart grid concepts and pilots

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***Abstract*--A large number of smart grid pilots are initiated worldwide to explore the potential of smart grids. At this stage, there is a clear need to identify how the results of these pilots can be evaluated. To enable the use of the methodological approaches applied for the estimation of the costs and benefits of smart grids, the results need to be generalized based on specific input assumptions. To this end, it is required to unravel the input-output relationship between the smart grid input and the change in the consumers' load profile. Therefore, when evaluating smart grid pilots, it is important to take into account which smart grid input variables are used to stimulate load shifting. These input variables are defined by the smart grid concept, and reflect the objectives of the involved stakeholders. This paper describes the challenges of and requirements for the evaluation of smart grid concepts and pilots. Furthermore, the proposed evaluation method is illustrated by describing two different smart grid concepts and their pilot set-up.**

***Index Terms*--Demand side management, distributed energy resources, load forecasting techniques, smart grids.**

I. Introduction

Worldwide a large number of smart grid pilots are initiated. Up to 2012 already 281 smart grid pilots are set up across 30 European countries, accounting for a total investment of €1.8 billion [1]. As there are various categories of benefits and beneficiaries of smart grid functionalities, pilot concepts are generally unique in a specific setting. To identify costs and benefits involved in smart grid pilots, frameworks are developed to define the impact for the entire electricity system and society, providing amongst others formulas for the monetization of benefits of smart grids, for its different functionalities [2], [3].

In [4] the societal costs and benefits associated with a large scale introduction of smart grids in the Netherlands are quantified, based on the various functionalities of smart grids. In [5] the potential of smart grids in the Netherlands is studied from the perspective of a distribution system operator, in this case the possibility to control flexible loads is used to optimize the utilization of the grid. Both studies, [4] and [5], assess the implications of introducing smart grids over a longer period, until 2050 and 2040 respectively. Over this length of time, data is hard to predict on core issues, such as (i) the energy production mix (e.g. penetration of renewables) and (ii) the energy demand (e.g. penetration of different loads). Therefore, a scenario-based methodology is applied in both studies to address the uncertainties related to long term (load) forecasting. It is estimated that by implementing smart grids in the Netherlands costs savings for society as a whole can vary between 35% and 67% [4], depending on the scenario for the future energy system. Amongst others, smart grids lead to costs savings due to (i) avoided grid investments, (ii) avoided grid losses, (iii) more efficient use of and (iv) avoided investments in central generation capacity, and (v) reduced imbalance. In [5] it is estimated that due to smart grids investment costs for distribution system operators can be reduced with 45% to 72%, depending on the scenario for the future energy system.

Important input factors for both studies are, besides the scenarios, assumptions with respect to energy savings and load shifting capacity of residential households due to the introduction of smart grids. In [4] it is assumed that due to smart grids there will be 4% energy savings, 4% daily peak shaving and 16% incidental peak shaving (i.e. 12 hours per year), and in [5] it is assumed that 10% of the future residential electricity demand is flexible and on top of that there is the flexibility of heat pumps and Electric Vehicles (EVs). In both studies the flexibility is used to reduce the peak, which means that e.g. 10% flexibility results in 10% peak reduction. These assumptions regarding the available flexibility at residential households are based on literature studies.

In Fig. 1 a simplified illustration of the approaches used in [4] and [5] is provided, the load profiles *with* a smart grid (dark grey box) are constructed based on an optimal deployment of assumed available flexibility due to the introduction of smart

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grids. To model load profiles *with* and *without* a smart grid, a bottom-up approach is often applied, considering the penetration and load of certain appliances individually.

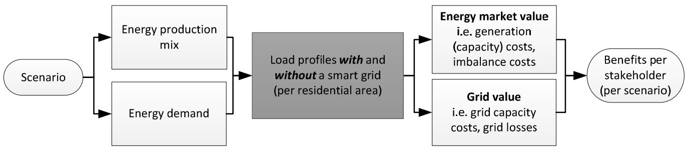

Fig. 1. Simplified illustration of the approach used for estimating the benefits of smart grids per scenario and per stakeholder, based on both [4] and [5].

Despite the large number of smart grid projects initiated worldwide, still there is not much known about what is the mobilized flexibility in the different pilots, and what exactly is the behavior of this flexibility. In [1] and [6] overviews are provided of the set-up and current status of the various smart grid pilots initiated worldwide. Comprehensive evaluation of these pilots is important as this can result in significant costs savings and impact increase when smart grids are implemented on a large scale.

At this stage there is a clear need to identify how the results of these pilots can be evaluated. A uniform approach to this end is required, as a lot of smart grid initiatives are generally unique in a specific setting. For example, various different approaches are used to influence electricity consumption: feedback on consumption is provided, dynamic pricing schemes are applied, enabling technology (e.g. smart appliances) is used, or automation is applied [7]. Furthermore, different stakeholders and beneficiaries are involved to stimulate load shifting. Using the pilot results as an input for the previously described scenario-based methodologies, provides a uniform approach to evaluate different smart grid concepts and pilots. In this case, load profiles *with* a smart grid are constructed based on the pilot results. This makes it possible to compare the output, i.e. the benefits of different smart grid concepts under similar conditions. Furthermore, this approach enables the validation of the assumptions done e.g. in [4] and [5].

II. Quantifying Flexibility

Some studies already give a general impression about the unlocked flexibility due to the introduction of smart grids, see also [8] and [9]. In this case, flexibility is often defined as the average percentage of peak load reduction. However, to enable the use of a scenario-based methodology to assess and compare the benefits of different smart grid concepts, an average percentage of peak reduction is not sufficient input. That is, because this approach requires that the results are generalized based on specific input assumptions. Identical scenarios should be used as an input for the evaluation of the results of the different pilots, as shown in Fig. 1. Therefore, it is necessary to find out (i) *what* the flexibility is, and (ii) *how* the flexibility is being deployed. Once these two aspects are known, it is possible to quantify flexibility in such a way that it becomes clear what the input-output relationship is that exist between flexibility and the variables that influence this. Consequently, this relationship can be used to generalize smart grid pilot results based on specific input assumptions.

In this part, both aspects of flexibility will be discussed. Consequently, a method is proposed to evaluate the results that the various smart grid pilots generate. Finally, this approach is illustrated by describing two different smart grid concepts and their pilot set-up, namely (i) PowerMatching City and (ii) Your Energy Moment.

A. Available Flexibility

The future energy demand, that depends on the future penetration of different loads, plays a major role in *what* the flexibility is. Due to e.g. an increase in the penetration of EVs and heat pumps, flexibility is expected to increase, as also the potential benefits of smart grids [5]. To this end, pilot results should be generalized based on the future penetration of the appliances used for load shifting. For example, if a smart grid pilot only focuses on the flexibility of EVs, its future impact and associated costs and benefits should be in line with the expected (future) penetration rate of EVs, or if the flexibility of heat pumps is only measured during winter periods, results should be adjusted for every season. Once it is clear *what* is the flexibility, the results of pilots can be generalized using identical scenarios (i.e. penetration rates) as input for the evaluation.

B. Deployment of Flexibility

The future energy mix plays a role in the deployment of the available flexibility, and thereby also in the monetization of the benefits. For example, due to an increase in renewables energy market prices are expected to become more volatile [10], which offers increasing opportunities for energy suppliers to stimulate load shifting. If these renewables are installed locally this also offers increasing possibilities for distribution system operators to use flexibility to locally match demand and supply, minimizing transport of electricity and reducing network peak loads. As there are various categories of benefits and beneficiaries of smart grids, flexibility can be deployed in different ways, i.e. energy suppliers and network operators can both stimulate load shifting. In [11] different optimized EV load curves are shown, and it can be concluded that the load profiles differ significantly when different optimization objectives are applied. For example, using the flexibility of EVs to reduce imbalance leads to higher peak loads in the network. Also, with an increase in renewables the difference between optimization based on decreasing peak loads and optimization based on day-ahead energy market prices is likely to increase [11]. Therefore, when defining the benefits of smart grids, it is important to know *how* flexibility is deployed. The smart grid concepts defines how the objectives of the involved stakeholders are translated into smart grid input variables to influence the load. Consequently, using the smart grid pilot results, it should become clear how exactly these smart grid ‘signals’ influence the load. Consequent step is to unravel what will be the impact of future developments in the power system on these signals: on the usage of the flexibility.

C. Generalizing Smart Grid Pilot Results

The future energy production mix and the future energy demand are of influence on *what* the flexibility is and *how* this flexibility is being deployed. Using the scenario input, future energy market prices (*price profiles*) and network loads (*load profiles*) can be defined. Both these price and load profiles are essential inputs for load control strategies. For example, if flexibility is used to reduce peak loads, time periods in which future peak loads occur should be identified, consequently the flexibility of different appliances to reduce load during these periods should be assessed.

To evaluate different smart grid concepts, the pilot results should be used to define how the demand side, the load profiles, can change due to a specific smart grid concept, shown by the dark grey box in Fig. 2. Flexibility should be quantified in such a way that it becomes clear how load profiles react on price profiles and (peak) load profiles. This flexibility and its dependencies should be quantified over time, as flexibility can be time critical. The latter is also of importance for dimensioning networks, an average percentage of flexibility does not guarantee that at critical peak moments this flexibility is available.

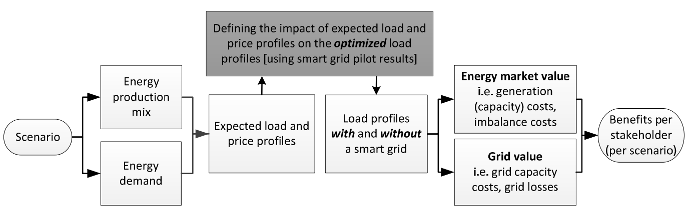

Fig. 2. Illustration of the suggested evaluation approach to define the benefits of different smart grid concepts. The dark grey box is used to match the scenario input with the pilot output, based on the evaluation of the pilot results.

III. Evaluation of the Pilot Results

To define the benefits of smart grids, the effects of load profiles *with* and *without* a smart grid need to be assessed and compared. Using the pilot results, i.e. the metered data in the pilot, the load change due to the pilot can be quantified. It should become clear what the relationship is between the change in the consumers’ electricity use and the factors that determine that change. Once this input-output relationship is known, it is also possible to define how the load profiles *with* a smart grid are in different scenarios.

Important for the evaluation, is to clarify what portion of the load change is due to the pilot rather than due to other unrelated factors, such as changes in weather patterns [12]. To this end, load forecasting techniques can be used to evaluate the results. Load forecasting techniques are used to predict load based on various input factors, and these techniques are already an integral part in efficient planning, operation and maintenance of a power system [13].

A. Short Term Load Forecasting Techniques

Load forecasting can be done on several time scales; from minutes to decades. For the evaluation of smart grid pilots it is important to quantify the effects of varying variables during the day, as it is expected that smart grid input factors will also influence load profiles during the day. Therefore, Short Term Load Forecasting (STLF) techniques are most suitable. STLF is often applied by utilities to forecast loads for the coming 24 hours, based on an hourly resolution [14]. Using the metered data from pilots as input data for modeling, STLF techniques can be used to model load profiles *with* a smart grid as well.

Different techniques can be applied for STLF, in [13] a classification of methods is provided, and in [14] different methods are described in detail. Compared to other STLF techniques, multiple regression provides an unambiguous interpretation of the results. For the evaluation of smart grid pilots, this is important as it should be possible to distinguish between what portion of the load change is due to the pilot, rather than due to other unrelated factors [12]. Generally STLF multiple regression models include predictor variables for: temperature, daytime and day of the week [14]. When evaluating pilot results, it is important to include the smart grid input used to stimulate load shifting as a variable in the model as well. For example, if a dynamic tariff is used to stimulate load shifting, this tariff can be included as a predictor variable. Consequently, multiple regression determines the parameters for each predictor variable. The parameters define to what extent each variable influences the load. In (1) the generic form for multiple regression is shown:

$$Y(X) = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \varepsilon \qquad (1)$$

where β_0 and β_i are the parameters that are determined by the regression analysis, X_i the predictor variables, ε the independent normally distributed random error variable, and Y the variable that needs to be predicted, i.e. the load.

Using STLF to model the pilot results, requires data for training. Due to changing weather patterns, there is need for data covering at least every season. When modeling load profiles *with* a smart grid, using STLF, the model incorporates the input-output relations of flexibility, e.g. the impact of dynamic tariffs on flexibility. Consequently this model can be used to define the effects of different tariffs on the load. Thereby, it is also possible to assess the impact of different scenarios on load profiles *with* a smart grid.

The metered data of a reference group can also be used to build a STLF reference model. Consequently, both models can be used to define load profiles *with* and *without* a smart grid using different input, e.g. simulating different scenarios. Using both load profiles the benefits of smart grid concepts can be monetized by using the previously described methodology (Fig 2).

IV. Case Study: PowerMatching City and Your Energy Moment

This part will focus on the evaluation of two smart grid pilots recently launched in the Netherlands, namely (i) PowerMatching City (phase-II), and (ii) Your Energy Moment. First, both smart grid concepts will be introduced, addressing also how the objectives of the involved stakeholders are translated into smart grid input variables to influence the load. Both concepts are different in a way that consumer interaction is essential in the pilot Your Energy Moment, whereas in PowerMatching City enabling technology and load automation is applied to mobilize flexibility. Due to the different pilot set-ups, different smart grid input variables need to be considered for the evaluation of the pilot results. This chapter is concluded by discussing these differences and their impact on the evaluation process.

A. PowerMatching City

In the second phase of PowerMatching City, which started in 2011, the living lab of phase-I is scaled up, involving now 40 households [15]. The active cluster in PowerMatching City phase-II consists of micro-CHPs, heat pumps and washing machines, these appliances are able to automatically interact with internal market prices [15].

In the pilot, a multi-agent system, based on the PowerMatcher technology, is applied [15]. This technology is based on the microeconomic theory of a general equilibrium, using a bottom-up electronic market mechanism. All appliances are represented by an agent, that is entrusted with the optimization of the device's objective. Every agent defines a bid that represents the allocated power for a given market price range. The appliances act according to their bid and the established market equilibrium price. However, this market equilibrium price is subjected to the objectives of various stakeholders involved in the pilot. Therefore, *how* flexibility is being deployed depends on the market dynamics and applied optimization strategies of the involved stakeholders. In the pilot the load of each individual appliance is measured separately, making it possible to derive the response of each device to market dynamics individual.

In PowerMatching City phase-II different power system participants are involved. Therefore, the pilot is considered multi-objective. The deployment of flexibility is influenced by the objective of the distribution system operator, i.e. to minimize local network peaks, and the objective of the energy supplier, i.e. to minimize its costs on the various energy markets and to minimize its imbalance (using either an active or passive approach [16]). Furthermore, the deployment of flexibility is influenced by the consumer proposition. In the pilot two consumer propositions are active, consumers can either give priority to locally produced renewable electricity, or to low-cost electricity, based on day-ahead energy market prices.

Summarizing the above, the load of each appliance is influenced by (i) the objective of the device itself (e.g. keeping temperature within limits), (ii) the consumer proposition (using low-cost electricity or locally produced renewable electricity), (iii) the objective of the DSO (minimize peak loads), (iv) the objective of the energy supplier (minimize costs on the various energy markets and reduce imbalance). All these variables, can influence the market equilibrium price, and thereby the load of the various appliances active in the cluster.

What the flexibility in PowerMatching City phase-II is, is defined by the bid curves the various appliances generate. If a device is flexible, the allocated power will differ for varying market prices. For example, if the temperature is within boundaries, a heat pump can decide to go on if market prices are low (e.g. ~1 kW), or go off if market prices are high (0 kW). By aggregating all bid curves, the total cluster flexibility can be defined for a certain time period. In Fig. 3 (*top*), the total flexibility is illustrated, using the minimum and maximum cluster power according to the aggregated bid curve.

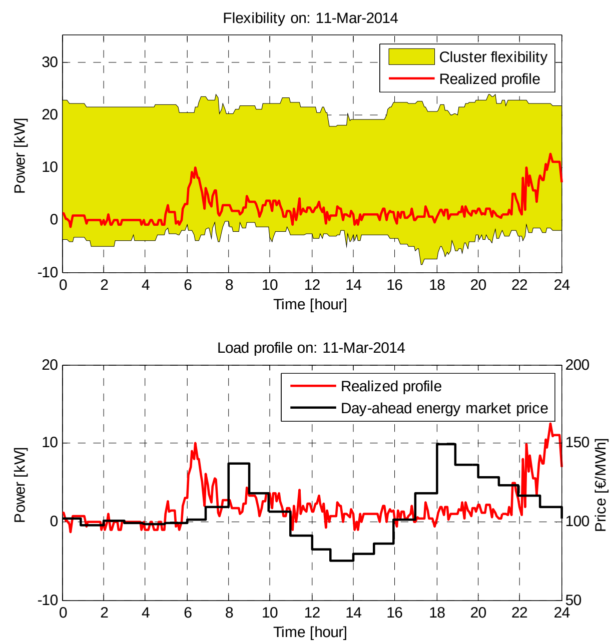

Fig. 3. Illustration of the pilot results of PowerMatching City (11-03-2014), *top:* available cluster flexibility based on the aggregated cluster bid curve, *bottom:* realized cluster load profile plotted against the day-ahead energy market price.

How the flexibility is being deployed depends on the applied optimization strategies, all previously mentioned smart grid input variables influence the market equilibrium price, and thereby influence the deployment of flexibility. For example, in Fig. 3 (*bottom*), one of the input variables is shown, i.e. the day-ahead energy market price, however the effect of this input variable is also influenced by the other applied optimization strategies, e.g. that of the consumer proposition or the distribution system operator. Furthermore, the flexibility is subjected to weather circumstances, daytime and day of the week. When quantifying the total effect of PowerMatching City, all these variables need to be taken into account.

Once it is clear how the load is influenced by the pilot concept, the pilot output for different future scenarios can be generated. In this case, the input used can be different energy market prices and different time periods of peak loads (Fig. 2). Consequently, the load profiles *with* a smart grid can be scaled up or down according to the penetration rates characterized by different scenarios. In order to define the benefits of PowerMatching City for the different directions in which the energy transition can developed

B. Your Energy Moment

The pilot Your Energy Moment (Jouw Energie Moment), which was launched by the end of 2012, focusses on changing consumer electricity consumption behavior. To enable this, financial incentives are provided. The pilot participants receive a dynamic tariff, which consists of (i) a dynamic energy tariff, and (ii) a dynamic network tariff, from the energy supplier and network operator respectively. In general tariffs are high during the evening, when peak loads occur, and low during the midday, to simulate the consumption of locally produced electricity.

Each household is equipped with a smart appliance, i.e. either a smart washing machine or a smart dryer, which optimizes its consumption by adjusting its starting time within the time frame set by the consumer, taking into local electricity production or dynamic tariffs. The difference between taking into account local production or dynamic tariff depends on the consumer proposition. Also in this pilot, consumers can give priority to locally produced renewable electricity, or to low-cost electricity. They can choose their proposition on their interactive wall display. This display also provides feedback on the consumers' electricity consumption and production, and it the informs the consumer about the dynamic tariffs.

In Your Energy Moment consumer interaction is the key factor [17]. As it is yet unknown how consumers will interact with the home energy management system applied in the pilot, simulations models need to be used to define the relationship between the smart grid input used, i.e. (i) the dynamic tariff and (ii) information on local generation, and the output, i.e. the realized load. In Fig. 4 an example of the pilot results is show. To define to what extent the load is influenced by the dynamic tariff and the local production, a multiple regression can be used which incorporates these smart grid input variables, as well as other relevant input variables (i.e. weather circumstance, daytime and day of the week). For an accurate model, data is required which covers at least every season. Consequently, a similar model can be generated using the smart meter data of a reference group. In the latter case it is expected that there will be no relationship between the dynamic pilot tariff and local production, as load profiles *without* a smart grid in general are best modeled by only considering only weather variables, daytime and day of the week [14]. By using the STLF model of the load *with* the Your Energy Moment smart grid, load profiles for various scenarios can be generated. The change in electricity demand due to a changing scenario can be predicted by means of the transformed dynamic tariff as input for the model (Fig. 2).

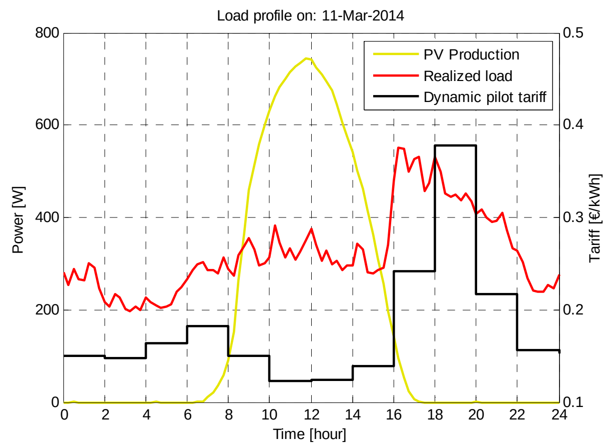

Fig. 4. Illustration of the pilot results of Your Energy Moment (11-03-2014), the pilot output is the realized load, the input used to stimulate load shifting is the dynamic tariff and local generation (i.e. PV production). The load profile is based on the average of 77 households in the 'Muziekwijk' in Zwolle.

C. Generalizing Smart Grid Pilot Results

In this part, two different pilot concepts were discussed. In order to compare the potential benefits, the described scenario-based methodology to asses smart grid benefits can be applied. However, in this case the results need to generalized based on the scenario input. To do so, the input-output relationship between the smart grid variables and the change in load profiles should become clear.

Different variables are used in both pilots to influence the load. Due to the multi-agent PowerMatcher technology applied in PowerMatching City, information on *what* the flexibility is can be derived from the appliances' bid curves. *How* the flexibility is deployed depends on the different optimization strategies of the involved stakeholders.

In Your Energy Moment, consumer interaction is the key factor, therefore *what* the flexibility per appliance is, is not measured (e.g., in the form of a bid curve). In the pilot the penetration of appliances is known (results of consumer questionnaires), and information on the deployment of flexibility can be derived from the measured data, shown in Fig. 4.

V. Conclusions

A large number of smart grid pilots are initiated worldwide to explore the potential of smart grids, up to 2012 already 281 smart grid pilots are set up across 30 European countries. At this stage, there is a clear need to identify how the results of these pilots can be evaluated.

To enable the use of the methodological approaches applied for the estimation of the costs and benefits of smart grids, the results need to be generalized based on specific scenario input assumptions. To this end, it is required to define *what* the flexibility is, and *how* the flexibility is being deployed. Using the pilot results, the input-output relationship between the smart grid input and the change in the consumers' load profile should be quantified. This can be done by using load forecasting techniques, e.g. smart grid variables can be included as predictor variables in a multiple regression model used for STLF.

For the evaluation of smart grid pilots, it is therefore essential to take into account which smart grid input variables are used to stimulate load shifting. These input variables are defined by the smart grid concept, and reflect the objectives of the involved stakeholders.

The proposed method for evaluating smart grid concepts and pilots, was illustrated by describing the smart grid concept and pilot set-up of both PowerMatching City and Your Energy Moment. Due to differences in the pilot set-ups and applied technologies, smart grid input variables differ, and thereby also the measured data differs. For both pilots, the relevant input variables were distinguished, and pilot results were illustrated. Addressing all essential aspects for the evaluation of smart grid concepts and pilots.

VI. Discussion

When using STLF to model load, the accuracy of the prediction model needs to be considered. Especially when the outcomes are used to compare the load *with* and *without* the application of smart grids; meaning that the accuracy of both profiles needs to be carefully considered when quantifying flexibility. When the accuracy of the STLF model is lacking and the flexibility is limited, this could result in situations in which there is no statistical significance for the change in the consumers' load due to the smart grid concept. In this case other models should be considered to unravel the effect of the pilot. However, then it might not be possible to generalize smart grid results based on input factors.

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